Real-Time Dynamics of Quantized Vortices in a Unitary Fermi Superfluid

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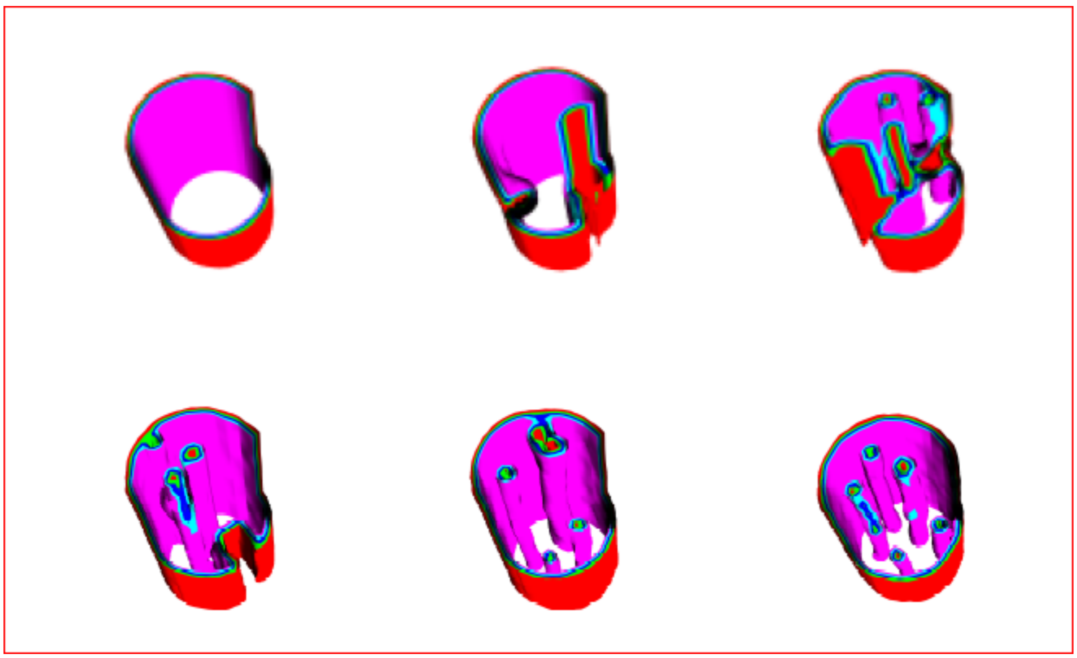
Superfluidity is a surprising manifestation of a quantum phenomenon discovered for the first time a century ago. In 1911 the Dutch physicist Kamerlingh Onnes observed that an electric current passed through mercury, which was cooled down to almost absolute zero (the lowest temperature possible, see http://en.wikipedia.org/wiki/Absolute_zero) shows no loss of power or in other words no electric resistance (see http://en.wikipedia.org/wiki/Superconductivity). Usually, when an electric current is passed through a conductor some of its energy is lost as it heats up the metal, as in old incandescent electric bulbs. A related phenomenon, the superfluidity of helium 4 was discovered in 1937 (see http://en.wikipedia.org/wiki/Superfluid). The superconductivity and superfluidity are quantum mechanical phenomena in systems of very large number of microscopic particles which one can observe with the ``naked eye." Only in 1957 three American theoretical physicists, John Bardeen, Leon Cooper and John Schrieffer provided the first compelling theoretical explanation of how superconductivity of metals occurs. Superfluidity is indeed a quite ubiquitous phenomenon, which by now has been put in evidence in many systems, from ultracold clouds of atoms, to atomic nuclei, neutron stars and so called high temperature superconductors. The microscopic particles which form these systems are of two types, fermions and bosons. One can pile bosons together in principle without limit and that leads to the so called Bose-Einstein condensation predicted by Einstein in 1925 and observed only in 1995 (see http://en.wikipedia.org/wiki/Bose-Einstein_condensate). Fermions on the other hand obey the Pauli Exclusion Principle (see http://en.wikipedia.org/wiki/Pauli_exclusion_principle), which states that two identical particles (such as electrons in metals) cannot be in the same quantum state simultaneously. In spite of having such vastly different quantum properties an ensemble of either fermions or bosons can become superfluid. Work for superfluidity and superconductivity has been recognized in Nobel prizes to almost two dozen individuals (Kamerlingh-Onnes, Landau, Kapitza, Bardeen, Cooper, Schrieffer, Abrikosov, Ginzburg, Leggett, Lee, Osheroff, Richardson, Bednorz, Muller, Esaki, Giavaer, Josephson, Cornel, Wieman, Ketterle).

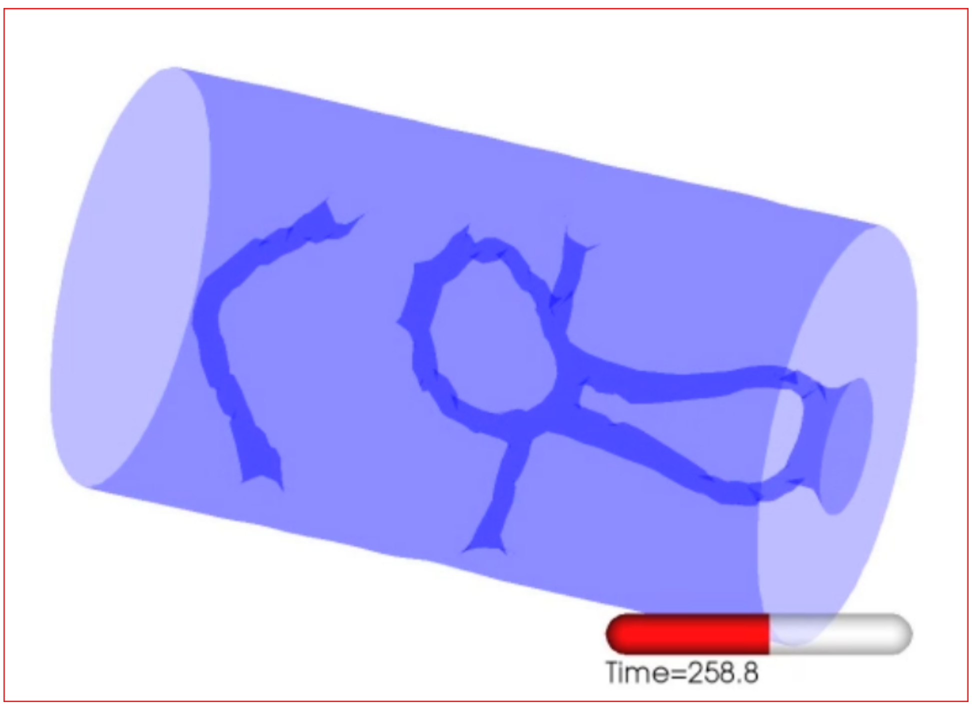
Until recently it was impossible to describe theoretically the real time dependent behavior of fermionic superfluids due to several reasons: 1) a theoretical framework describing the dynamics of strongly interacting fermions in the superfluid state was missing; 2) even though an approximate theory existed for weakly interacting fermions, the number of equations one had to solve was essentially infinite; 3) even if one would try to throw such an approximate theory on a computer, until recently there were no computers capable of handling such a complex problem. Unlike a bosonic superfluid, the mathematical framework needed for a fermionic superfluid is about a hundred thousand times more complex.



In the figure above one can see consecutive frames showing the formation of quantum vortices in a can filled with a superfluid and stirred with a rod and a ball (see http://www.phys.washington.edu/groups/qmbnt/UFG/).

All these three hurdles have been overcome in this work and the existence of the largest supercomputer for open science Jaguar PF at the National Center for Computational Sciences at Oak Ridge National Laboratory in Tennessee (see http://www.nccs.gov/) provided the authors with the ultimate tool to solve this problem. Jaguar PF consists of almost a quarter of a million processors and in order to perform the calculation reported in the Science article the group of five researchers used, for this project and related nuclear physics projects, about 70 million CPU hours in 2010, equivalent to about 8,000 years of running on a single laptop.

With this new set of 21st century tools, the authors simulated for the first time the evolution in real time of a fermionic superfluid in the full three-dimensional space. The authors were able to observe a number of unexpected phenomena, in particular the fact that when stirred vigorously a fermionic superfluid could retain its ``magic'' quantum properties. Liquid helium on the other hand, which is a bosonic superfluid, loses its superfluid properties rather quickly when energetically stirred. A superfluid also rotates unlike a bucket of water. If one rotates a bucket of superfluid very slowly the bucket will rotate, but the superfluid will remain motionless. If one rotates the bucket faster however one observes the formation of quantum vortices (somewhat similar to miniscule tornadoes, see http://en.wikipedia.org/wiki/Quantum_vortex).



When the number of such quantum vortices becomes large a new quantum phenomenon predicted by Feynman in 1955 (see http://en.wikipedia.org/wiki/Quantum_turbulence) sets in, when these quantum vortices, which look like noodles, cross and reconnect in a manner similar to DNA recombination as in figure above (see http://en.wikipedia.org/wiki/Genetic_recombination).